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THE MARK 101 FLUX COMPRESSION GENERATOR: DEVELOPMENT PROGRESS*

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ABSTRACT

The Mark 101 explosive flux compression generator is a line-initiated, helical generator that offers the possibility of a theoretical $dL/dt \geq 0.5\ \Omega$. The design and initial tests were reported by Fowler, et al.[1] and Freeman, et al.[2] Subsequent to the early results, which demonstrated current gains of only ~1.2:1, the generator design was modified and now includes a low-density foam staging layer between the PBX 9501 explosive and the aluminum armature and a vinyl coating on the stator winding. This redesigned Mark 101 has an initial working inductance of 5.36 μH and a load inductance of 0.60 μH. The lossless current gain of this unit is 9.9:1, and the estimated practical gain is ~5.5. Experiments have been performed using SF_6 and vacuum as the insulating media between the armature and stator. Measured current gains of ~5.0:1 have been achieved. The maximum measured dI/dt of $\sim 1.2 \times 10^{11}$ Amps/sec and V of ~62 kV were significantly less than expected during high-current tests. However, a case motion experiment has shown that the armature is probably disintegrating during the last few microseconds of the armature run. Thus, the configuration of the staging layer between the explosive and the armature has been the subject of study. The results of the generator tests are presented.

INTRODUCTION

The theoretical promise of the Mark 101 flux compression generator, as reported by Fowler et al.,[1] is to provide a device that is capable of delivering a $dL/dt > 0.5\ \Omega$ and voltages of the order of 0.5 MV. However, the experimental results at that time[2] were not very encouraging, since current gains of only 1.2:1 had been achieved. However, given suggestions from several sources,[3,4,5] the Mark 101 FCG (flux compression generator) was modified to use a low-density foam staging layer between the explosive and the armature to reduce the first shock on the armature. Also, the bare copper stator winding was coated with vinyl to further reduce the possibility of premature shorting in the generator volume. The modification of the armature diameter, to accommodate the 1.27-cm-thick staging layer, and a reduction to a 4-wire, 7.5-turn stator

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geometry from the earlier 8-turn configuration resulted in a generator inductance of ~5.36 μH. Also, the passive inductive load was lengthened slightly to permit a more robust current connection, so its inductance is ~0.60 μH. Figure 1 illustrates the current physical configuration. Thus, the ideal Mark 101 current gain is 9.9:1. However, one must note that since this a simultaneously-initiated FCG, the magnetic diffusion losses are not limited by utilizing an ever smaller fraction of the conductors through the run of this generator. Therefore, our best theoretical estimate of the current gain for the Mark 101 is ~5.5:1.

EXPERIMENTAL TESTS

A total of four experimental tests have been performed with the Mark 101 in the newer configuration. The major differences from the earlier tests[2] are that the armature inner diameter is 22.86 cm rather than 20.32 cm, a 1.27-cm-thick, 0.1-g/cm^3 polyurethane foam staging layer has been placed between the explosive and the armature, the stator winding has been vinyl coated to prevent premature shorting to the armature, and the 4-wire, 8-turn stator has been changed to a 4-wire, 7.5-turn configuration to add geometrical stability during assembly. Also, three of the four tests utilized SF_6 at ambient pressure as an insulating environment, rather than vacuum. One low-current test was performed with SF_6, and one used a vacuum of 5×10^{-5} torr. Both "high"-current experiments utilized SF_6. One of these had a stator fabricated with hard-drawn copper wire, and the other had completely annealed copper wire, to examine the possibility of stator wire breakage.

A total of eight diagnostic probes were used on each experiment. A Rogowsky loop was located at the cable input to the FCG, and a second loop was positioned around the central, current-carrying rod of the inductive load. Each of the four upper attachment stubs for the stator had a Rogowsky loop around it to measure the current through the four wires that comprised the stator winding. Unfortunately, there is some indication that a mechanical impulse from these stubs may have prematurely destroyed some of these current measurements during times of interest. Finally, the generator voltage and the relative ground voltage were measured with resistive dividers.

DISCUSSION OF RESULTS

The inner radius of the stator is 17.78 cm, and the average outer radius of the armature is 11.83 cm. Thus, the expansion radius of the armature is 5.95 cm, 6.03 cm at the input end. Since the explosive is PBX-9501, with a detonation velocity of 0.88 cm/μs, the armature will achieve an outward velocity of ~0.45 cm/μs. Therefore, the run time of the Mark 101 generator is now ≈13.4 μs to contact the input end of the stator, where there is a small uncertainty due to the interaction of the foam layer. Since the armature at the output end of the stator must still expand another centimeter at a slightly slower velocity, the total FCG run is ~16 μs. However, with the open geometry in this area, the burnout is not very sharp. Using a combination of analytical[1] and computational techniques, an initial current of 100 kA would result in a final current of ~551 kA, or a current gain of 5.5:1 as noted earlier. The maximum dI/dt would be ~3.3×10^{11} A/sec and maximum voltage across the load would reach ~162 kV. If one assumes an initial current of 280 kA, then a final current of ~1.57 MA, a maximum dI/dt of ~9.2×10^{11} A/sec, and a peak load voltage of ~460 kV are predicted from the same models. However, in the higher current case the predicted results should be somewhat more optimistic than the low-current case since differences in flux losses and possible conductor motion are not taken into account.

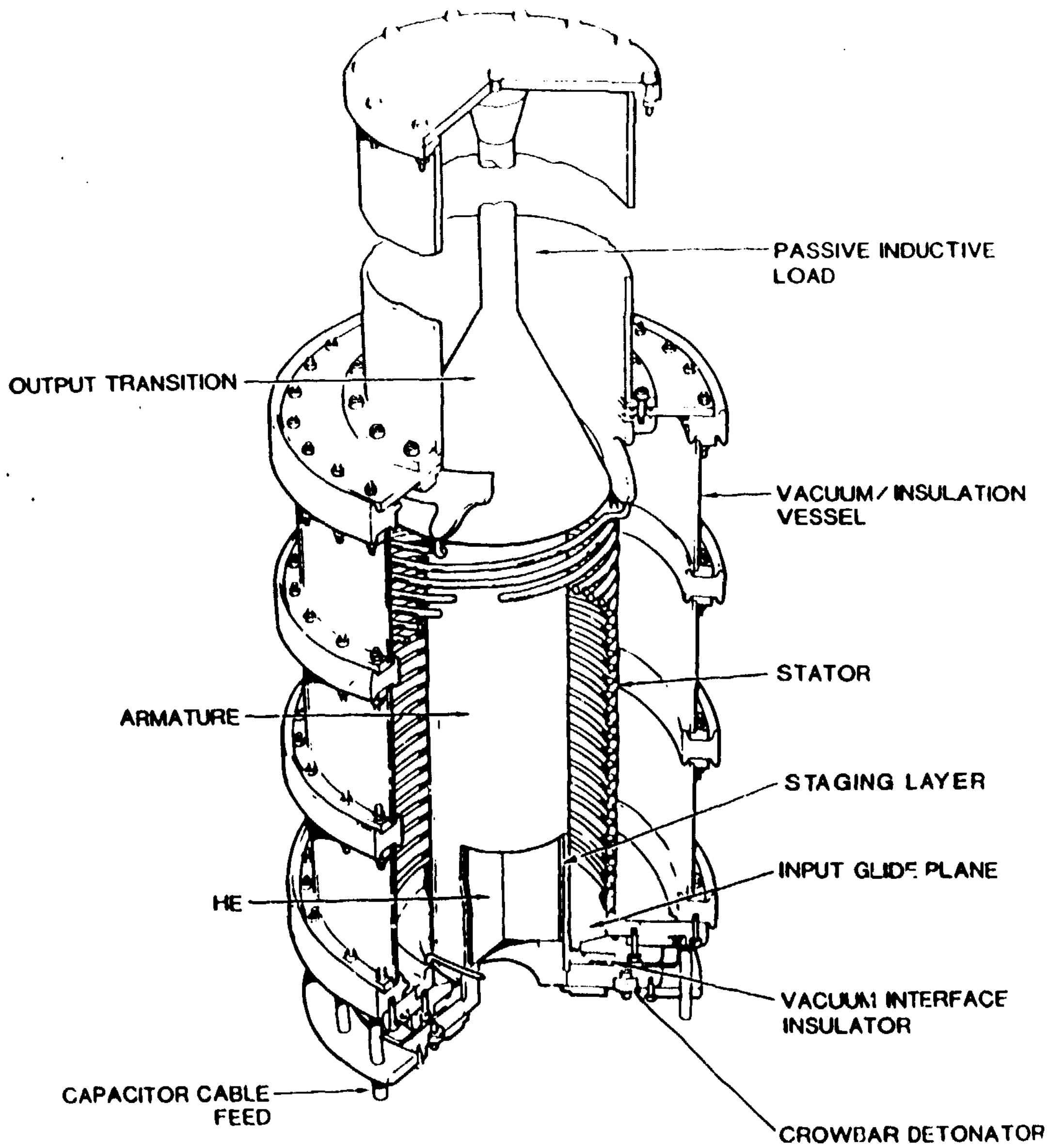

Fig. 1. This drawing of the Mark 101 generator shows the key components, including the location of the foam staging layer.

The low-current test of the Mark 101 that used SF_6 was primed with an initial current of ~120 kA from a 3000 μF capacitor bank with a 6.3-kV charge voltage. The loading time and detonator-actuated crowbar-contact time were ~222.9 μs, but first armature motion was delayed for ~5.0 μs to provide a clear signal for generator action. The maximum current produced was ~600 kA, Fig. 2, which represents a current gain of ~5.0:1. A maximum dI/dt of ~8.7 × 10^{10} A/sec was inferred by summing the four Rogowsky loops. The peak voltage measured was ~39 kV. Figure 3 shows the dI/dt and voltage measurements with a magnified time scale. The low-current, vacuum experiment produced much lower results. The initial current was ~128 kA, the final current was ~316 kA, the maximum dI/dt was ~1.2 × 10^{10} A/sec, and the peak voltage was ~38 kV. Thus, the current gain on this second low-current shot was ~2.47:1. In the first test, one will note that the generator performance, indicated by dI/dt, drops off about 2.0 μs before first contact with the stator, while the vacuum case, Fig. 4, lost performance at ~9.5 μs relative to the same event.

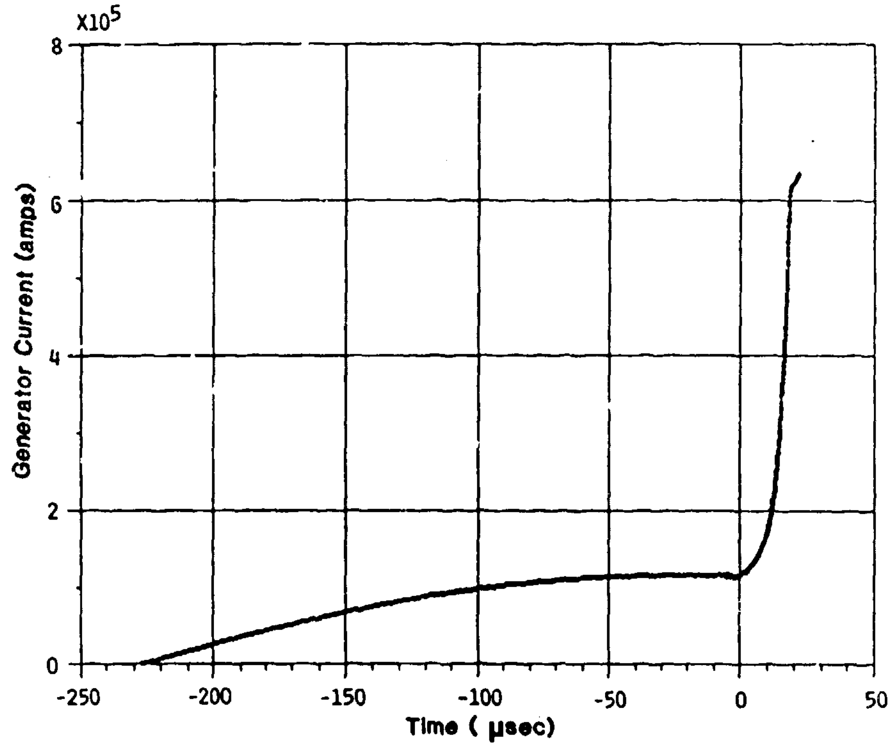

Fig. 2. The current trace for the low-current, SF_6 insulated experiment shows a multiplication of ~5.0:1.

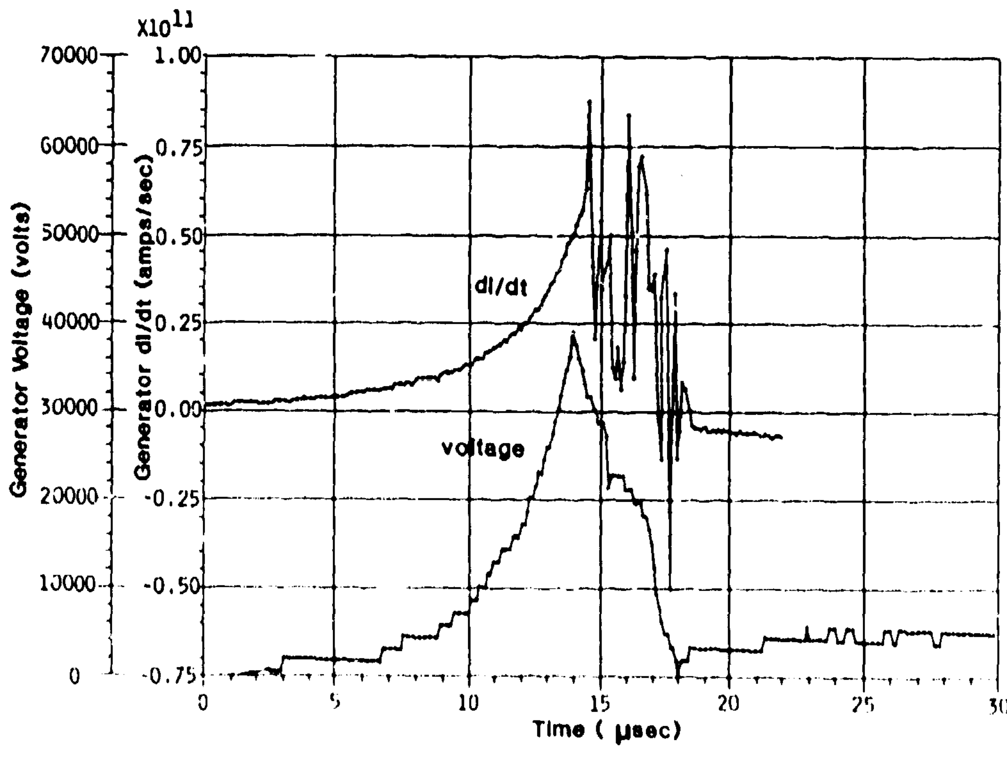

Fig. 3. The voltage and dI/dt traces for the low-current, SF_6 insulated experiment show maximum values of ~39 kV and ~8.7×10^{10} A/s.

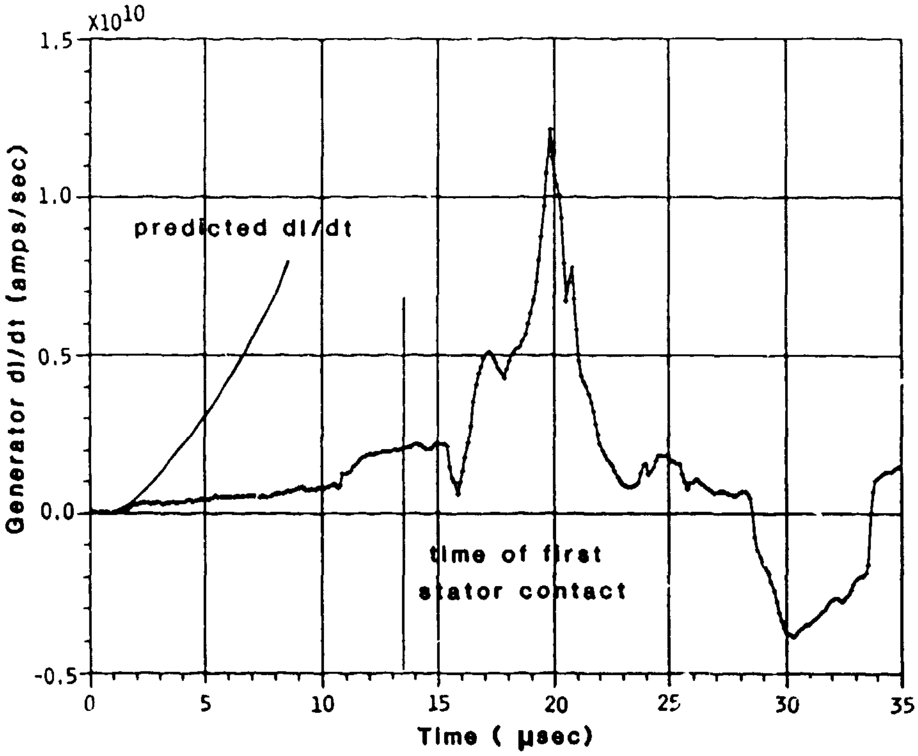

Fig. 4. The dI/dt trace for the low-current, vacuum insulated experiment shows a maximum value of $\sim 1.2 \times 10^{10}$ A/s. It also emphasizes the significant reduction in performance relative to the predicted behavior.

The two high-current experiments were identical except that the second stator was fabricated using fully-annealed copper wire, rather than hard-drawn copper. The first of these tests was initialized with a current of ~300 kA with the 3000-μF capacitor bank charged to 16.0 kV. The final current was ~1.24 MA, the maximum dI/dt was $\sim 1.15 \times 10^{11}$ A/s, and the peak voltage was ~60 kV. Figures 5 and 6 show these measurements. The current gain was reduced from the low-current tests to ~4.15:1. The second high-current test, that was intended to look for stator breakage problems in the previous shot, performed almost identically. The initial current was ~380 kA, the maximum current was ~1.58 MA, the peak dI/dt was $\sim 1.8 \times 10^{11}$ A/sec, and the maximum voltage was ~62 kV, no statistical difference. These characteristics are shown in Figs. 7 and 8. The current gain in this unit was ~4.16:1, which, while seemingly better, is well within the errors of the experiment. In both of these experiments, a significant drop in dI/dt occurred ~2.0 μs before first stator contact.

While the theoretical current gain performances are, relatively considered, the easier parameters to achieve, the comparisons are revealing. All three of the SF_6 tests performed reasonably well with respect to net current gain. The best result is the low-current shot where 91% of the calculated current gain was measured. Also, both of the high-current tests achieved current gains of ~75% of the theoretical number, even though the models, as stated earlier, did not take into account the higher skin losses associated with the higher currents. However, the low-current, vacuum experiment only achieved a current gain of ~45% of the theoretical prediction during the nominal generator run. After nominal "burnout," additional current gain was measured. Also, the performance in the maximum dI/dt in the low-current, SF_6 shot was reduced by a factor of ~3.8 relative to the theoretical estimate. The two high-current tests did demonstrate significant differences in this parameter. The hard-drawn copper stator was down by a factor of ~7.6, but the fully annealed stator had a maximum dI/dt that

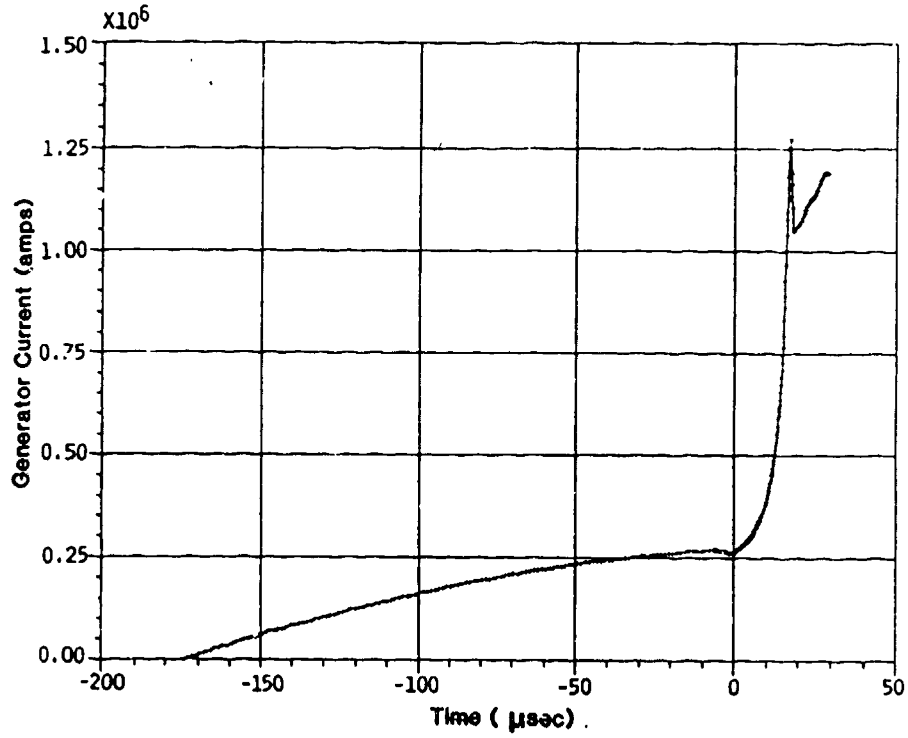

Fig. 5. The current trace for the high-current, SF_6 insulated experiment, which utilized a hard-drawn copper wire stator, shows a maximum current of ~1.24 MA.

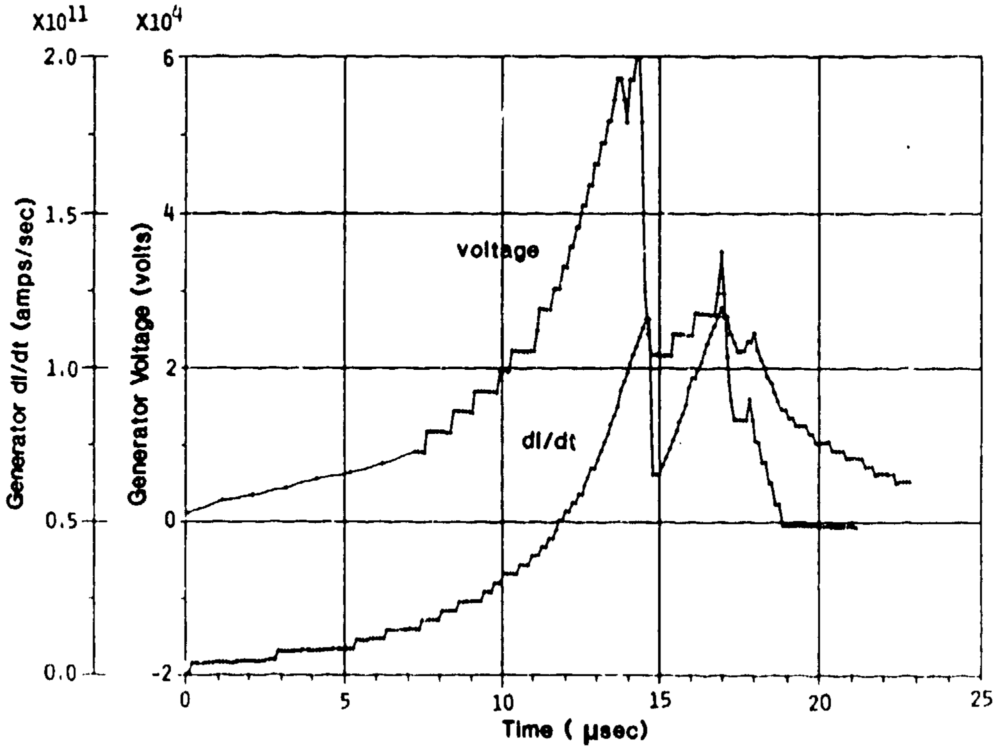

Fig. 6. The voltage and dI/dt traces for the high-current, SF_6 insulated experiment which shows maximum values of ~60 kV and ~1.15×10^{11} A/s.

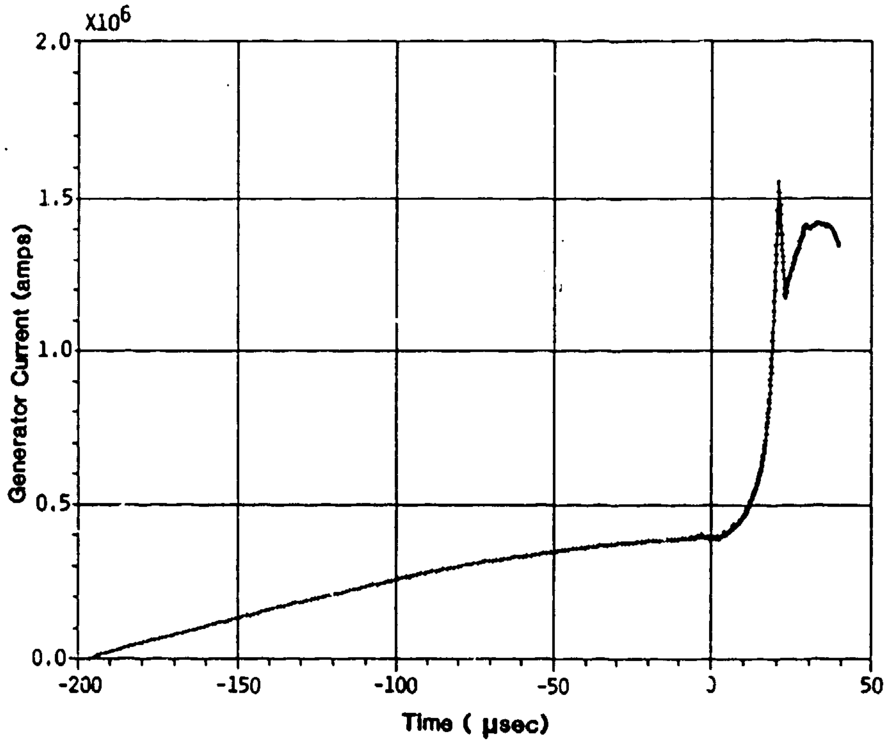

Fig. 7. The current trace for the high-current, SF_6 insulated experiment, which utilized an annealed copper wire stator, shows a maximum value of ~1.58 MA.

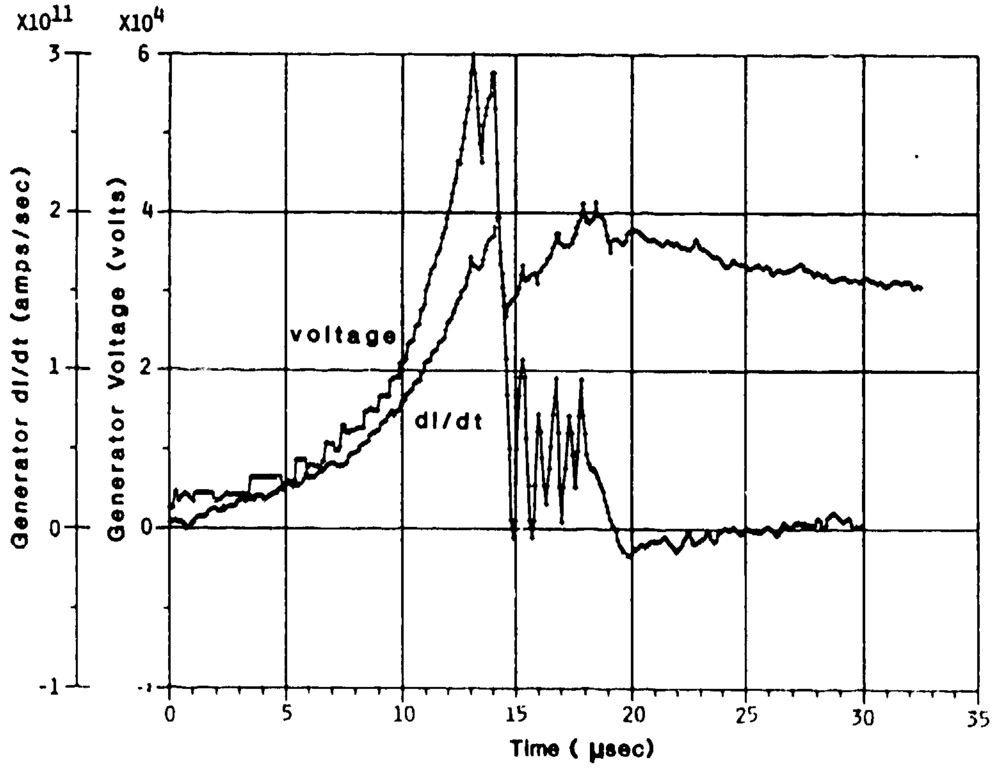

Fig. 8. The voltage and dI/dt traces for the high-current, SF_6 insulated experiment, which utilized an annealed copper wire stator, shows maximum values of ~62 kV and ~1.8 × 10^{11} A/s.

was reduced only by a factor of ~5.1, very similar to the low-current test. Given the consistency of the voltage measurements on the low-current and high-current experiments, and their significantly different performances, one is forced to doubt that the measurement desired is actually being made. For example, a short in the input cables to a stray ground could compromise this measurement. Then, the relative times in the generator runs when the respective performances were degraded are very similar for the three SF_6 shots, while the vacuum test experienced degradation significantly earlier in time. Finally, a case motion experiment may provide a significant understanding for the lack of late-time performance in these tests. This test demonstrated that the integrity of the armature is severly compromised in the last few microseconds of its expansion.

CONCLUSIONS

Since the last experimental report on the Mark 101 generator, this FCG has been modified and shown to work as a generator. In fact, in one low-current test, a current gain of ~91% of the theoretical prediction has been measured. Nevertheless, in all of the recent series of experiments the performance of the Mark 101 has been seriously degraded in the last few microseconds of the armature motion. There is evidence that the staging layer, installed to reduce the strength of the initial breakout shock on the armature and to reduce microjetting from the aluminum surface, may be nucleating jetting and causing significant armature breakup later in the expansion of the aluminum cylinder. If such a hypothesis is correct, then the vacuum performance would suffer more quickly in time than the SF_6 shots. Of course, other explanations are also conceivable. The voltage measurement inconsistencies represent another question. To address this issue, the cable feed to the Mark 101 has been redesigned to place the input current feed point much closer to the "natural ground" of this FCG. This modification has not been tested and awaits a solution to the staging/smoothing layer study. The major point is that unlike the first report on the Mark 101 FCG, we now have a working flux compressor with some remaining questions and problems to resolve.

REFERENCES

[1] C. M. Fowler, R. S. Caird, B. L. Freeman, and S. P. Marsh, "Design of the Mark 101 Magnetic Flux Compression Generator," Fourth International Conference on Megagauss Magnetic Field Generation and Related Topics, C. M. Fowler, R. S. Caird, and D. J. Erickson, Eds., Plenum Press, New York and London, pp. 433–439 (1986).

[2] B. L. Freeman, C. M. Fowler, J. C. King, A. R. Martinez, J. B. VanMarter, L. R. Veeser, and J. E. Vorthman, "Testing of the Mark 101 Magnetic Flux Compression Generator," Fourth International Conference on Megagauss Magnetic Field Generation and Related Topics, C. M. Fowler, R. S. Caird, and D. J. Erickson, Eds., Plenum Press, New York and London, pp. 441–445 (1986).

[3] M. Cowan, private communication at the Fourth International Conference on Megagauss Magnetic Field Generation and Related Topics, 1986.

[4] G. A. Shvetosv, private communication at the Fourth International Conference on Megagauss Magnetic Field Generation and Related Topics, 1986.

[5] J. R. Asay, "Effect of Shock Wave Risetime on Material Ejection from Aluminum Surfaces," Sandia National Laboratories Report SAND77-0731, September 15, 1977.